

# The energy dependence of the chaoticity $\lambda$ parameter from BEC of $\pi$ -pairs produced in $pp$ collisions

Gideon Alexander<sup>a,1</sup> and Vitalii A. Okorokov<sup>b,2</sup>

*a) School of Physics and Astronomy, Raymond and Beverly Sackler Faculty of Exact Sciences, Tel-Aviv University, 69978 Tel-Aviv, Israel*

*b) National Research Nuclear University MEPhI (Moscow Engineering Physics Institute), 115409 Moscow, Russia*

## Abstract

The  $\sqrt{s_{pp}}$  behavior of the chaoticity parameter  $\lambda$ , derived from Bose–Einstein Correlations (BEC) of pion-pairs produced in  $pp$  collisions, is investigated. Considered are the one and three dimensions (1D, 3D) of the BEC analyzed in terms of a Gaussian and/or Exponential distributions. A marked difference is observed between the  $\lambda$  dependence on energy in the 1D and the 3D analyzes. The experimental data are examined in terms of the relation between the pion cluster of sources and the BEC dimension  $R$  which in turn are deduced from the charged outgoing particle multiplicity. While in this approach the general decrease with energy of the 1D  $\lambda$  is accounted for it fails to represent the few 3D  $\lambda$  data which are seen to remain constant with energy above  $\sim 200$  GeV.

October 31, 2016

---

<sup>1</sup>Email: gideona@post.tau.ac.il

<sup>2</sup>Email: VAOkorokov@mephi.ru; Okorokov@bnl.gov

# 1 Introduction

With the recent operation of the Large Hadron Collider (LHC) at CERN the opportunity to study the Bose–Einstein Correlations (BEC) of identical bosons at very high hadron-hadron collision energy has been opened [1–6]. In particular the energy dependence of the BEC dimension  $R$  has recently been investigated and was found to increase with  $\log(\sqrt{s_{NN}})$  both in proton-proton ( $pp$ ) and in heavy ion ( $AA$ ) collisions [7–9]. In the present work we investigate the energy behavior of the chaoticity parameter  $\lambda$  in  $pp$  collisions which determines the strength of the measured BEC effect. To this end we utilize the relation between the BEC dimension  $R$ , the number of pion source clusters and  $\lambda$ . We further stipulate that the pion source clusters are proportional to the average charged particle multiplicity produced in the hadron reactions.

The BEC is measured in terms of the two identical particle correlation function

$$C(p_1, p_2) = \frac{\rho(p_1, p_2)}{\rho_0(p_1, p_2)}, \quad (1)$$

where  $p_1$  and  $p_2$  are the 4-momenta of the two hadrons,  $\rho$  is the two particle density function and  $\rho_0$  is the two particle density function in the absence of the BEC effect. This  $\rho_0$  is often referred to as the reference sample against which the BEC is measured. There are several ways to construct  $\rho_0$  which were adopted by the different BEC experiments [10]. These and the different background conditions and the variety of BEC analysis methods should be appraised when their physics implications are determined. Throughout this work we assume that the BEC background is well accounted for and that one can safely ignore the influence of the long range correlations on the  $\lambda$  properties.

## 2 The one dimension BEC analysis

Among the various BEC representations one of the frequently used in the one dimension (1D) analysis of hadrons emerging from a sphere volume, is the Goldhaber parametrization of a static Gaussian source in the plane-wave approach [11], namely

$$C_{Gauss}(Q) = 1 + \lambda_{Gauss} e^{-Q^2 R_{Gauss}^2}, \quad (2)$$

which assumes for the particles emitter a spherical volume with a radial Gaussian distribution. The second often used parametrization, which assumes a radial Lorentzian distribution of the source, is given by

$$C_{Expo}(Q) = 1 + \lambda_{Expo} e^{-QR_{Expo}}, \quad (3)$$

which generally was found at low  $Q$  values, e.g.  $Q \leq 0.1$  GeV, to fit better the measured BEC distribution than the Gaussian parametrization [12]. In both representations  $Q^2 = -(p_1 - p_2)^2$  is the difference squared of the 4-momentum vectors of the two correlated identical bosons. The  $\lambda$  factor, also known as the chaoticity parameter, lies in the range between 0 and 1.

In the 1D analysis the relation between  $R_{Gauss}$  and  $R_{Expo}$  dimensions can be evaluated from the requirement that the first  $Q$  moment in a given BEC distribution will be equal whether it

is treated by a fit to a Gaussian distribution or to an Exponential one, namely

$$\frac{\int_{Q_1}^{\infty} Q e^{-R_{Gauss}^2 Q^2} dQ}{\int_{Q_1}^{\infty} e^{-R_{Gauss}^2 Q^2} dQ} = \frac{\int_{Q_1}^{\infty} Q e^{-R_{Expo} Q} dQ}{\int_{Q_1}^{\infty} e^{-R_{Expo} Q} dQ} . \quad (4)$$

This relation remains essentially the same as long as the upper integration value is higher than 2 GeV. The dependence of  $R_{Expo}/R_{Gauss}$  on the lower integration limit  $Q_1$  is shown in Fig. 1. In the case that  $Q_1 = 0$  GeV one obtains the known relation

$$R_{Gauss} = \frac{R_{Expo}}{\sqrt{\pi}} . \quad (5)$$

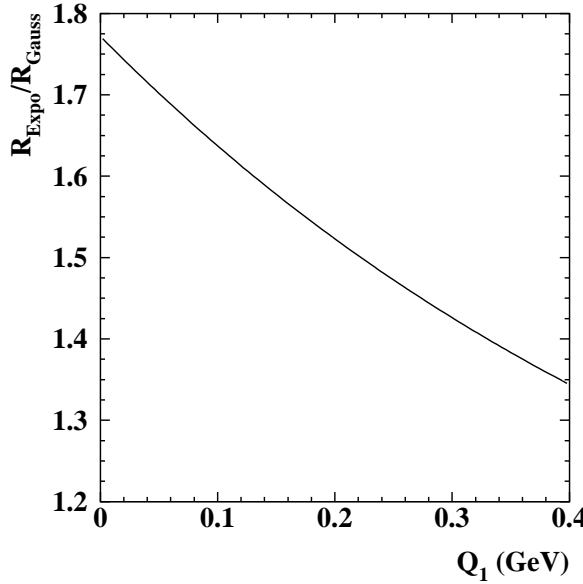


Figure 1:  $R_{Expo}/R_{Gauss}$  as a function of the lower integration limit  $Q_1$  in Eq. (4) and the upper integration value is  $\geq 2$  GeV.

A relation between  $\lambda_{Gauss}$  and  $\lambda_{Expo}$  can in principle be estimated by considering the relations

$$\int_{Q_1}^{Q_2} \lambda_{Expo} e^{-Q R_{Expo}} dQ \simeq \int_{Q_1}^{Q_2} \lambda_{Expo} e^{-Q R_{Gauss} \sqrt{\pi}} dQ \simeq \int_{Q_1}^{Q_2} \lambda_{Gauss} e^{-Q^2 R_{Gauss}^2} dQ , \quad (6)$$

where in the range between  $Q_1$  and  $Q_2$  GeV the Gaussian and the Exponential BEC parametrizations fit equally well the measured  $Q$  distribution. In this case for the values of  $Q_1 = 0$  and  $Q_2 = \infty$  GeV one finds that

$$\lambda_{Gauss} = \frac{2\lambda_{Expo}}{\pi} . \quad (7)$$

Experimentally it has been found that the chaoticity parameter depends on several of the data properties such as the average particle pair transverse momentum,  $\langle k_T \rangle$ , and in particular on the outgoing charged particle multiplicity  $N_{ch}$ . Hence the additional division of the experimental measured  $\lambda$  data into different categories is advisable before attempting a meaningful comparison with a model prediction. For this reason we have here, unlike in a former

preliminary study [13], considered two distinct  $pp$  collision data sample, the first without any multiplicity restrictions labeled by MB (Minimum-Bias events) and the second the High Multiplicity events, labeled by HM. The measured values of  $\lambda_{Gauss}^{MB}$  and  $\lambda_{Gauss}^{HM}$  are given in Table 1.

The measured ratios  $\lambda_{Expo}/\lambda_{Gauss}$ , evaluated from Table 1, are significantly different from that of  $\pi/2$  given by Eq. (7) as they are lying in the neighborhood of the value 2. The relation between the parameter pairs  $(R_{Gauss}, \lambda_{Gauss})$  and  $(R_{Expo}, \lambda_{Expo})$  obtained in BEC fits to the measured  $Q$  distributions are studied in some details in Ref. [23] where the  $\lambda_{Expo}/\lambda_{Gauss}$  obtained ratios are matched much better to the measured ones inferred from Table 1.

### 3 The $R$ and $\lambda$ dependence on the $pp$ energy

It has been shown that in the 1D BEC there exists a relation between the dimensions  $R_{n=1}$  and  $R_{n>1}$ , where  $n$  is the number of independent similar emitting pion source clusters [24], namely

$$R_n = n \frac{\lambda_n}{\lambda_1} R_{n=1} . \quad (8)$$

which relates the one sources dimension  $R_1$  at low energies with its value  $R_n$  for  $n$  identical cluster of sources. The  $\lambda_1$  and  $\lambda_n$  parameters are the chaoticity values respectively for  $n = 1$  and  $n$  clusters. Since we limit ourselves to the study of the behavior of the chaoticity parameter with energy it is sufficient to evaluate the energy dependence of the ratio  $\lambda = \lambda_n/\lambda_1$ .

Recently the one dimension  $R$  dependence on the  $pp$  collision center of mass energy energy was observed to increase from low energies of less than 100 GeV to those reached by the LHC at 7 TeV. This rise was fitted [7] to yield

$$R(s) = \left\{ (1.64 \pm 0.11) + (0.14 \pm 0.02) \ln(\sqrt{s/s_0}) \right\} R_{n=1} , \quad (9)$$

where  $s$  is in  $\text{TeV}^2$  units and  $s_0 = 1 \text{ TeV}^2$ .

It has further been shown that the experimental BEC results are depending only slightly, if at all, on the rapidity<sup>1</sup> extent used in the accumulation of pion-pairs data sample [25]. Thus  $R$  is essentially independent of the rapidity domain used in the experimental BEC analyzes and as such should also be valid for the results obtained from particle tracks at the mid rapidity region.

The energy behavior of  $\lambda$  in terms of Eqs. (8) and (9) thus requires a solution of the equation

$$\left\{ (1.64 \pm 0.11) + (0.14 \pm 0.02) \ln(\sqrt{s/s_0}) \right\} R_{n=1} = n(s) \lambda R_{n=1} , \quad (10)$$

where  $n(s)$  is the number of source clusters which depends on energy in the chosen rapidity domain. As has been found that  $R$  increases with the average charged multiplicity  $\langle N_{ch} \rangle$  of the colliding hadrons and since our aim is to estimate the  $\lambda$  dependence on energy but not on its absolute value, it is sufficient to require that the number of source clusters is proportional to the average charged multiplicity.

---

<sup>1</sup>Throughout this work we refer to pseudorapidity by rapidity.

Table 1: Measured  $\lambda$  values obtained from the 1D Bose–Einstein correlations of two identical pion pairs produced in  $pp$  collisions using the Gaussian and/or the Exponential parametrizations according to Eqs. (2) and (3). The superscript MB and HM refer respectively to results from all events and from only high charged multiplicity events. Whenever the statistical and systematic errors were reported separately they were added in quadrature in the table.

1D BEC analyzes		The chaoticity $\lambda$ parameter		
Reference	$\sqrt{s}$ (GeV)	$\lambda_{Gauss}^{MB}$	$\lambda_{Gauss}^{HM}$	$\lambda_{Expo}$
[14]	7.21	$0.466 \pm 0.015$	$0.532 \pm 0.013$	—
[15]	26.0	$0.32 \pm 0.08$	$0.43 \pm 0.13$	—
[16]	31.0	$0.41 \pm 0.02$	$0.35 \pm 0.04$	—
[16]	44.0	$0.40 \pm 0.02$	$0.42 \pm 0.04$	—
[17]	58.1	$0.34 \pm 0.04$	—	—
[16]	62.0	$0.43 \pm 0.02$	$0.42 \pm 0.08$	—
[18]	63.0	$0.39 \pm 0.07$	—	$0.77 \pm 0.07$
[19]	63.0	$0.45 \pm 0.03$	—	—
[20]	200*	$0.35 \pm 0.04$	$0.36 \pm 0.04$	—
[4]	900	$0.35 \pm 0.03$	$0.31 \pm 0.03$	$0.55 \pm 0.05$
[12, 21]	900	$0.34 \pm 0.03$	—	$0.74 \pm 0.11$
[1, 2]	900	$0.315 \pm 0.014$	—	$0.63 \pm 0.03$
[1]	2360	$0.32 \pm 0.01$	—	$0.66 \pm 0.09$
[22]	7000	$0.65 \pm 0.05$	$0.66 \pm 0.07$	—
[12, 21]	7000	$0.33 \pm 0.02$	$0.25 \pm 0.02$	$0.53 \pm 0.05$
[2]	7000	—	—	$0.62 \pm 0.04$

\*The relative systematic uncertainty for  $\lambda$  is taken to be equal to the corresponding error associated with the BEC radius.

### 3.1 The $\lambda_{1D}$ energy dependence

A compilation of  $\lambda_{Gauss}$  and  $\lambda_{Expo}$  deduced from the 1D BEC of pion-pairs produced in  $pp$  collisions is given in Table 1 ordered according to their  $pp$  energy. The measured 1D  $\lambda_{Gauss}$  are also plotted in Fig. 3 where the chaoticity values in the energy region of 20 to 60 GeV are seen to be scattered somewhat, most probably due to the different adopted experimental procedures as pointed out in Section 1. In spite of this, a general decrease with energy of the  $\lambda_{Gauss}$  values is apparent. Here it should be noted that the ALICE results at  $\sqrt{s} = 7$  TeV [22], which are outside the boundary of the figures are quite different from those of the ATLAS experiment [12] and also are far from being part of the general pattern of the  $\lambda(s)$  energy dependence.

To evaluate the  $\lambda_{Gauss}$  dependence on energy we follow the formalism outlined in Ref. [26] where the hadron-hadron collisions is contributed by two components. The first is the “hard” component, with a contribution fraction  $x$ , which is due to the number of binary collisions  $N_{coll}$ , and the remaining  $1 - x$  fraction originates from the number of participants  $N_{part}$  referred to as the “soft” processes. In the case of  $pp$  collisions one has  $N_{part} = 2$  and  $N_{coll} = 1$ ,

so that the number of outgoing charged particles per rapidity unit in  $pp$  can be noted as  $(dN_{ch}/d\eta)|_{\eta=0} = n_{pp}$  in accordance with [26].

In general in hadron collisions the BEC is analyzed in a rapidity range symmetric to its central value of  $\eta = 0$  and it is only slightly dependent, if at all, on the extent of the rapidity domain used in the analysis (see, e.g. Refs. [27, 28]). Thus one should expect that the charge particle multiplicity utilized in a BEC analysis, is approximately proportional to  $(dN_{ch}/d\eta)|_{\eta=0}$ .

For the energy dependence of the charged multiplicity mid-rapidity density we have considered three log and power series expressions [27, 29, 30] given by

$$\left(\frac{dN_{ch}}{d\eta}\right)\bigg|_{\eta=0} = \begin{cases} \sum_{i=0}^2 a_i \ln^i(s/s_0), & \text{(a)} \\ \sum_{i=0}^2 a_i \ln^i(s_a/s_0), & \text{(b)} \\ a_0(s/s_0)^{a_1}. & \text{(c)} \end{cases} \quad (11)$$

where  $s_a \equiv (\sqrt{s} - 2m_p)^2$  and  $m_p$  is the proton mass. The  $a_i$  are the free parameters which were determined from the data to yield the values given in Table 2. To note is that in Eq. (11) and in the subsequent formulas  $s$  is given in units of  $\text{GeV}^2$  and  $s_0 = 1 \text{ GeV}^2$ , unless otherwise specifically indicated.

Table 2: The free parameter values obtained for the rapidity density of charged multiplicity in  $pp$  collisions.

Reference	Eq.	$a_0$	$a_1$	$a_2$
[27]	(11a)	$2.5 \pm 1.0$	$-0.25 \pm 0.19$	$0.023 \pm 0.008$
[29]	(11b)	0.39	0.09	0.011
[30]	(11c)	$0.75 \pm 0.06$	$0.114 \pm 0.003$	—

In Fig. 2 are shown the energy dependence of the mid-rapidity charge particle densities according to Eq. (11) using their parameter values given in Table 2. As can be seen, the three Eq. (11) expressions agree among themselves in the energy range from  $\sqrt{s} \sim 30 \text{ GeV}$  up to of 8 TeV and as such do follow well the measured charge multiplicity density  $(dN_{ch}/d\eta)|_{\eta=0}$  in the range  $\sqrt{s} \sim 200 \text{ GeV}$  to 8 TeV. For our analysis we have chosen the parametrization given by Eq. (11c) which agrees well with the measured data further up to 13 TeV and quotes the smallest relative errors for its components. Thus we have

$$(dN_{ch}/d\eta)|_{\eta=0}(s) = (0.75 \pm 0.06)(s/s_0)^{0.114 \pm 0.003}. \quad (12)$$

Inserting  $n(s) = (dN_{ch}/d\eta)|_{\eta=0}(s)$  into Eq. (10) one obtains the following relation:

$$C \left\{ (0.67 \pm 0.18) + (0.14 \pm 0.02) \ln(\sqrt{s/s_0}) \right\} = \lambda \left\{ (0.75 \pm 0.06)(s/s_0)^{0.114 \pm 0.003} \right\}, \quad (13)$$

where  $C$  is a normalization factor. Solving  $\lambda$  from Eq. (13) one obtains

$$\lambda_{Gauss}(s) \simeq C \frac{(0.89 \pm 0.25) + (0.19 \pm 0.03) \ln(\sqrt{s/s_0})}{(s/s_0)^{0.114 \pm 0.003}}. \quad (14)$$

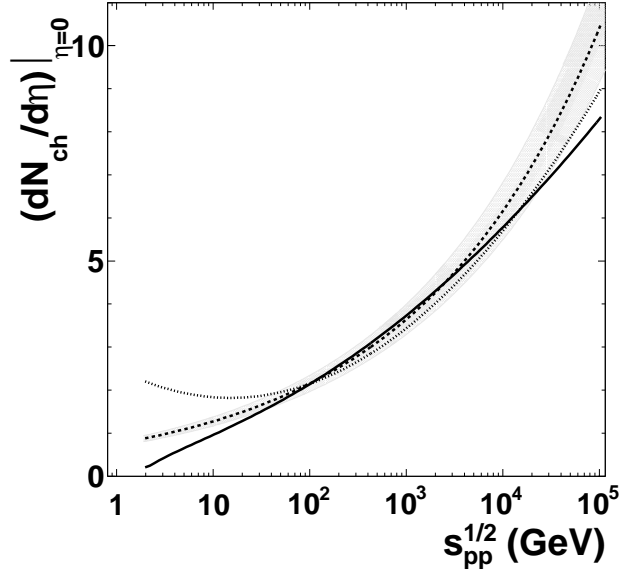


Figure 2: Energy dependence of pseudorapidity density of secondary charged particles produced in proton-proton and anti-proton-proton collisions at mid-rapidity ( $\eta = 0$ ). The dashed curve corresponds to the analytic form (11a) with parameters from [27], the solid line represents the modified log-series parametrization (11b) from [29] and the dotted curve is the power function (11c) from [30] with its uncertainty band.

In the present work the normalization of Eq. (13) was determined by requiring that our calculated  $\lambda$  will be equal to the experimentally well measured  $\lambda_{Gauss}$  values at 200 GeV [20] given in Table 1. This yielded for the MB and HM data samples respectively nearly the equal values of  $C_{MB} = 0.63 \pm 0.11$  and  $C_{HM} = 0.63 \pm 0.13$ .

The experimentally determined  $\lambda$  values are shown in Fig. 3 as a function of  $\sqrt{s}$  for  $pp$  collision data free of charged particle multiplicity limitation (left) and for only high multiplicity events (right). The data are compared in both figures with our normalized calculated estimations accompanied by a  $\pm 1$  s.d. band limits drawn by the dotted curves. As can be seen, our calculated  $\lambda_{Gauss}$  behavior with the  $pp$  energy is within 1 s.d in good agreement with the general decrease with energy of the measured chaoticity values obtained from the HM data sample. For the BEC deduced  $\lambda_{gauss}$  from the MB data sample our approach seem somewhat to deviate from the data at  $pp$  energies above  $\sim 1$  TeV. From this follows that in  $pp$  collisions at  $\sqrt{s} = 13$  TeV and in the current highest planned LHC energy of  $\sqrt{s} = 14$  TeV, the expected 1D  $\lambda_{Gauss}$  values for HM events should approach  $\sim 0.20$ .

### 3.2 The $\lambda_{3D}$ energy dependence

The BEC analysis in three dimensions (3D) is frequently represented in its Gaussian form by

$$C_{3D}(Q_{long}, Q_{out}, Q_{side}) = 1 + \lambda_{3D} e^{-(R_{long}^2 Q_{long}^2 + R_{out}^2 Q_{out}^2 + R_{side}^2 Q_{side}^2)}, \quad (15)$$

where the directions *long*, *out* and *side* are defined in the Longitudinal Center of Mass System (LCMS). (see e.g. Ref. [10]). The  $\lambda_{3D}$  measured values deduced from BEC carried out in  $pp$  collisions at center of mass energies of 200, 900 and 7000 GeV are listed in Table 3. At the

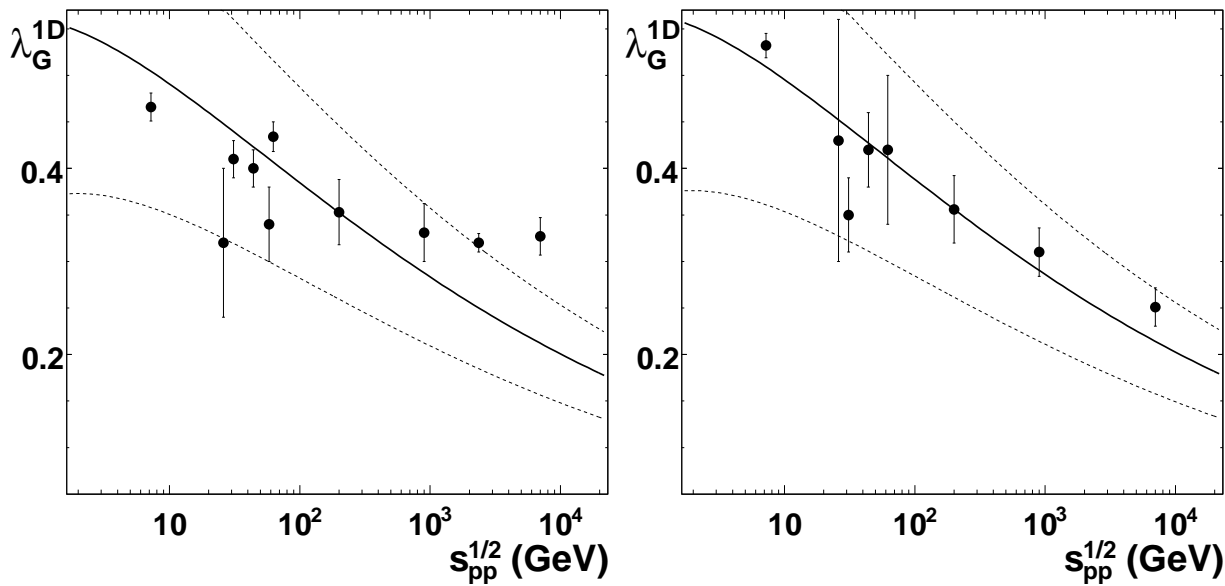


Figure 3: The 1D two-pion BEC results for  $\lambda_{Gauss}$  as a function of  $\sqrt{s}$ . The expected  $\lambda_{Gauss}$  dependence on energy calculated in this work is shown by the continuous lines normalized to the measured  $\lambda_{Gauss}$  at 200 GeV. The dotted lines represent its  $\pm 1$  s.d. limits. Left: Events without a charged multiplicity cut. The multiple  $\lambda_{Gauss}$  values at 900 was averaged as well as an average was taken of the  $\lambda_{Gauss}$  values at  $\sqrt{s} = 62 - 63$  GeV. Right: Measured  $\lambda_{Gauss}$  in high charged multiplicity events.

LHC energies as well as at  $\sqrt{s} = 200$  GeV there are only a qualitative indication for a smooth decrease of  $\lambda_{3D}$  with multiplicity together with a relative small dependence on  $k_T$  [5].

This  $k_T$ -dependence of the chaoticity parameter is studied in 3D BEC analyzes but not in the Gaussian representation of the 1D BEC studies [20]. As only  $\lambda_{1D}$  and  $\lambda_{3D}$  values derived at similar, or approximately, experimental conditions can be used for a meaningful comparison, the  $\lambda_{3D}$  values given in Table 3 were those obtained at the lowest  $k_T$ . Furthermore for a comparison purpose the chaoticity data shown in Table 3 are those deduced from the BEC analyzes of the high multiplicity  $pp$  collision data. As can be seen, the  $\lambda_{3D}$  values are higher at the LHC than the corresponding 1D  $\lambda_{Gauss}$  obtained at the same  $pp$  center of mass energy<sup>2</sup> and the ratio  $\lambda_{3D}/\lambda_{1D}$  indicates some growth with energy within their uncertainties.

## 4 Summary

The 1D BEC measured values of  $\lambda_{Gauss}$  and with them also the values of  $\lambda_{Expo}$ , show a general decrease with the  $pp$  collision energy in particular in the high charged multiplicity events which does point to an increase in the coherent pion production.

The approach adopted here, in which the dimension  $R$  and the multiplicity increase with the  $pp$  collision energy are correlated to the number of source clusters, yield a decrease of the 1D  $\lambda_{Gauss}$  with energy. The results of this approach agree well with experimentally 1D BEC deduced  $\lambda_{Gauss}$  values obtained from the high charged particle multiplicity data up to the  $pp$

<sup>2</sup>It should be noted that this conclusion is also valid if the estimation  $\lambda_{3D} \sim 0.49$  is used for the minimum bias events at the LHC energies based on the qualitative information from [5] together with corresponding values for  $\lambda_{1D}$  given in Table 1.



Table 3: A comparison between the  $\lambda_{3D}$  and  $\lambda_{1D}$  measured in the high multiplicity  $pp$  collision events.

3D BEC in $pp$ collisions		The measured $\lambda_{Gauss}$ in HM events		
Reference	$\sqrt{s}$ (GeV)	$\lambda_{1D}$	$\lambda_{3D}$	$\lambda_{3D}/\lambda_{1D}$
[20]	200*	$0.35 \pm 0.04$	$0.42 \pm 0.04$	$1.20 \pm 0.18$
[4, 5]	900	$0.31 \pm 0.03$	$0.42 \pm 0.04$	$1.35 \pm 0.18$
[5, 21]	7000	$0.25 \pm 0.02$	$0.42 \pm 0.04$	$1.68 \pm 0.21$

\*The relative  $\lambda$  systematic uncertainty is taken to be equal to the corresponding error of the BEC dimension.

multi-TeV energy region. As for the  $\lambda_{Gauss}$  obtained from event samples without any cut on the outgoing charged particle multiplicity, there is some discrepancy in the multi-TeV energy region between the data and the calculated model expectation

The chaoticity values extracted from the 3D Bose–Einstein correlations are significantly higher than those obtained in the 1D analyzes, and they seem to remain essentially constant at the high energy end of the currently available data.

## Acknowledgments

We would like to thank T. Csörgő, C. Pajares and E.K.G. Sarkisyan for helpful suggestions and comments.

## References

- [1] CMS Collaboration, V. Khachatryan et al., Phys. Rev. Lett. 105 (2010) 032001.
- [2] CMS Collaboration, V. Khachatryan et al., J. High Energy Phys. 0511 (2011) 029.
- [3] CMS Collaboration, CMS PAS FSQ-13-002, (2014).
- [4] ALICE Collaboration, K. Aamodt et al., Phys. Rev. D82 (2010) 052001.
- [5] ALICE Collaboration, K. Aamodt et al., Phys. Rev. D84 (2011) 112004.
- [6] ALICE Collaboration, K. Aamodt et al., Phys. Lett. B696 (2011) 328.
- [7] G. Alexander, J. Phys. G: Nucl. Part. Phys. 39 (2012) 085007.
- [8] G. Alexander and I. Ben Mordechai, J. Phys. G: Nucl. Part. Phys. 40 (2013) 125101.
- [9] V.A. Okorokov, Adv. High Energy Phys. 2015 (2015) 790646.
- [10] G. Alexander, Rep. Prog. Phys. 66 (2003) 481.
- [11] G. Goldhaber et al., Phys. Rev. Lett. 3 (1959) 181; *ibid.*, Phys. Rev. 120 (1960) 300.
- [12] ATLAS Collaboration, G. Aad et al., Eur. Phys. J. C75 (2015) 466.
- [13] G. Alexander, V. A. Okorokov, J. Phys.: Conf. Ser. 675 (2016) 022001.

- [14] E766 Collaboration, J. Uribe et al., Phys. Rev. D49 (1994) 4373.
- [15] NA23 Collaboration, J.L. Bailly et al., Z. Phys. C43 (1989) 341.
- [16] ABCDHW Collaboration, A. Breakstone et al., Z. Phys. C33 (1987) 333.
- [17] AFS Collaboration, T. Åkesson et al., Phys. Lett. B155 (1987) 128.
- [18] AFS Collaboration, T. Åkesson et al., Z. Phys. C36 (1987) 517.
- [19] SFM Collaboration, A. Breakstone et al., Phys. Lett. B162 (1985) 400.
- [20] STAR Collaboration, M.M. Aggarwal et al., Phys. Rev. C83 (2011) 064905.
- [21] I. Sýkora, Proceedings of the XXIII International Workshop on Deep-Inelastic Scattering and Related Subjects, PoS (DIS2015) 157.
- [22] ALICE Collaboration, B. Abelev et al., Phys. Lett. B739 (2014) 139.
- [23] V.A. Okorokov, *arXiv*: 1605.02927 [hep-ph] (2016).
- [24] P. Lipa, B. Bushbeck, Phys. Lett B 223 (1989) 465; B. Bushbeck, H.C. Eggers, P. Lipa, Phys. Lett. B481 (2000) 187; G. Alexander, E.K.G. Sarkisyan, Phys. Lett. B487 (2000) 215; Nucl. Phys. Proc. Suppl. 92 (2001) 211.
- [25] See e.g., NA49 Collaboration, S. Kniese et al., J. Phys. G: Nucl. Part. Phys. 30 (2004) S1073; *ibid.*, AIP Conf. Proc. 828 (2006) 473.
- [26] D. Kharzeev, M. Nardi, Phys. Lett. B507 (2001) 121.
- [27] CDF Collaboration, F. Abe et al., Phys. Rev. D41 (1990) 2330.
- [28] ALICE Collaboration, K. Aamodt et al., Eur. Phys. J. C65 (2010) 111.
- [29] A. Kumar et al., Eur. Phys. J. Plus 128 (2013) 45; *private communications*.
- [30] ALICE Collaboration, K. Aamodt et al., Phys. Rev. Lett. 105 (2010) 252301; ALICE Collaboration, J. Adam et al., *arXiv*: 1509.07541 [nucl-ex] (2015); *ibid.* Phys. Lett. B753 (2016) 319.